Food Production for Space:
A Review of Some NASA Activities

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Food Production Workshop, NASA ARC
September 2012

Human Life Support Requirements:

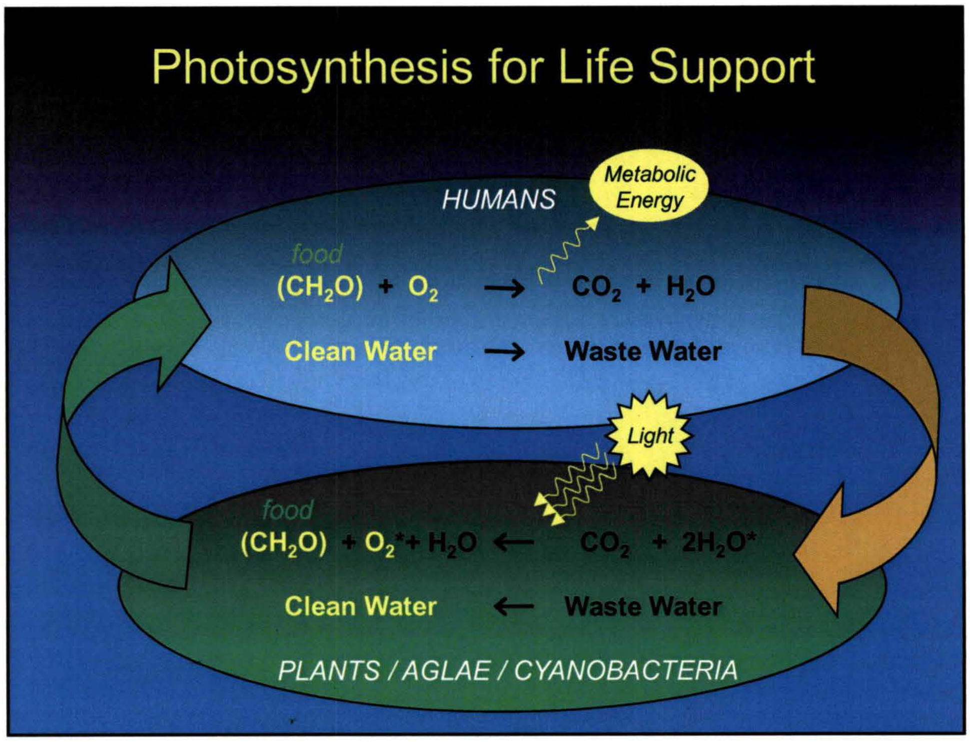
Inputs

	Daily Rqmt.	(% total mass)
Oxygen	0.83 kg	2.7%
Food	0.62 kg	2.0%
Water (drink and food prep.)	3.56 kg	11.4%
Water (hygiene, flush laundry, dishes)	26.0 kg	83.9%
TOTAL	***31.0 kg***	

Outputs

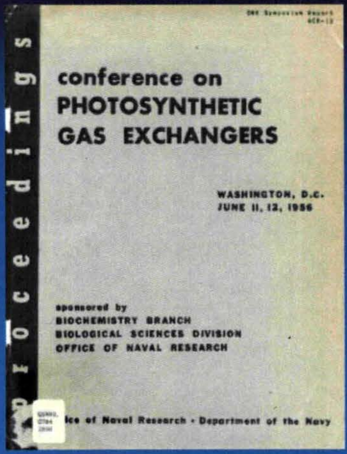
	Daily	(% total mass)
Carbon dioxide	1.00 kg	3.2%
Metabolic solids	0.11 kg	0.35%
Water	29.95 kg	96.5%
(metabolic / urine		12.3%)
(hygiene / flush		24.7%)
(laundry / dish		55.7%)
(latent		3.6%)
TOTAL	***31.0 kg***	

Source: NASA SPP 30262 Space Station ECLSS Architectural Control Document
Food assumed to be dry except for chemically-bound water.



1956: Photosynthesis for Life Support

US Navy looking at algae for O_2 production / CO_2 removal

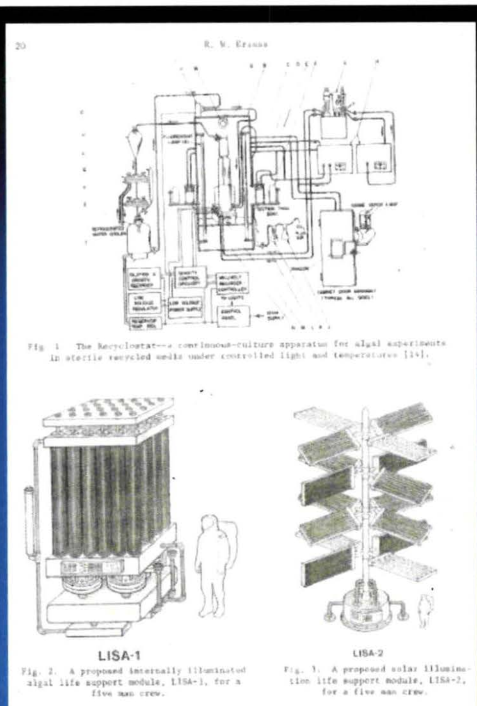


ATTENDANCE LIST

Mr. E. H. Allen, Bureau of Ships
Mr. Morris Alpert, Bureau of Ships
CAPT Harry Alvis, Bureau of Medicine and Surgery
Dr. William Arnold, Oak Ridge National Laboratory
Dr. James Bassham, University of California
CDR Charles B. Bishop, Undersea Warfare Branch, Office of Naval Research
LCDR George Breeden, Bureau of Ships
LCDR William I. Bristol, Bureau of Ships
Dr. Allan Brown, University of Minnesota
Dr. Dean Burk, National Institutes of Health
Dr. Melvin Calvin (Chairman), University of California
Mrs. B. H. Caminita, Biochemistry Branch, Office of Naval Research
CAPT E. H. Eckelmeyer, Jr., Naval Sciences Division, Office of Naval Research
Dr. Sidney Galler, Biology Branch, Office of Naval Research
Mr. A. S. Gates, Bureau of Ships
Dr. Harold B. Goteas, University of California
Mr. J. D. Gutmann, Bureau of Ships
Mrs. Helen Hayes, Biology Branch, Office of Naval Research
Mr. Roland Jackel, Chemistry Branch, Office of Naval Research
Dr. Robert Krauss, University of Maryland, College Park, Maryland
Mr. William McConnaughey, Naval Research Laboratory
LCDR L. V. Mowell, Bureau of Ships
Dr. Jack Myers, University of Texas
Mr. Leon Newman, Bureau of Ships
CAPT C. P. Phoebus, Office of Naval Research
Dr. Orr E. Reynolds, Biological Sciences Division, Office of Naval Research
CDR Trenton K. Ruebush, Office of Naval Research
Mr. Joseph Saunders, Medicine and Dentistry Branch, Office of Naval Research
Mr. Leo A. Shinn, Biochemistry Branch, Office of Naval Research
CDR E. T. Steigelman, Bureau of Ships
Mrs. Patricia Tenniswood, Microbiology Branch, Office of Naval Research
CDR D. E. Washburn, Bureau of Ships

Early Studies Focused on Algae and Cyanobacteria *(1950s and 1960s)*

- *Chlorella pyrenoidosa* TX71105 (thermotolerant 39°C)
- Other species of *Chlorella*, *Anacystis, Synechocystis, Scenedesmus*, *Synechococcus, Spirulina* were studied
- Development of culture systems (chemostats, turbidostats)
- Protocols for harvesting and nutrient replenishment
- Studies with animals (e.g., mice, monkeys) and humans
- Interest in Assimilation and Respiration Quotients (AQ and RQ)



Concepts for Algal Production Systems

(R.W. Krauss. 1962. Amer. J. Botany 49:425-435.)

Observations from Algae / Cyano Studies:

- Positives
  - high photosynthetic efficiency and biomass productivity
  - good volume efficiency
  - good energy efficiency--minimum wastage of light
- Negatives
  - difficulties with food processing / palatability
  - long-term, sustained production challenges
  - gas / liquid phase issues for μ-gravity
  - no transpiration advantage for water purification
  - not convenient for point source lamps

Costs of Life Support Options for Space

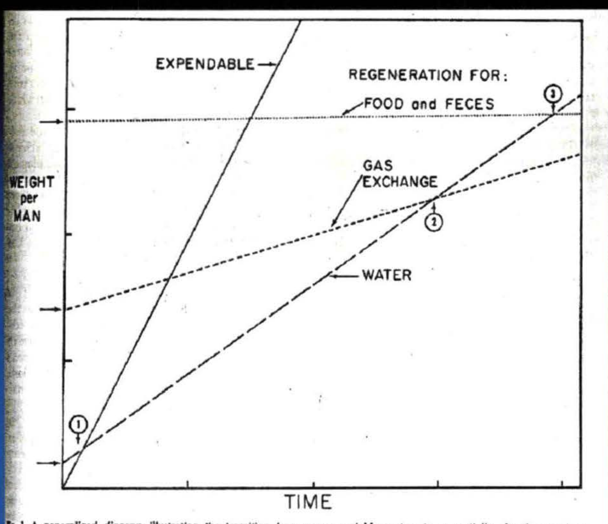
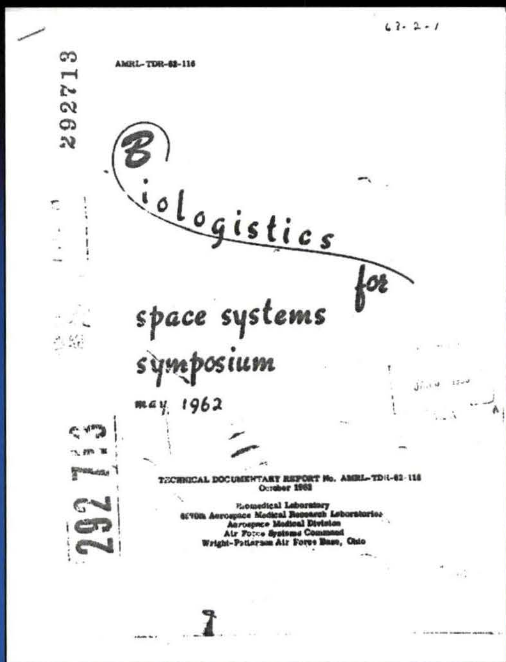


Fig. 1. A generalized diagram illustrating the transition from an expendable system to a partially closed ecosystem. Criteria of feasibility are represented by the times of the numbered crossover points designated for each of the succeeding regenerative steps: 1. water, 2. gas exchange, 3. food and feces. Arrows on the ordinate designate the fixed cost of processing equipment, including the energy source but not expendable fuel, needed for each regenerative step.

From: J. Myers. 1963. Space biology: Ecological aspects. Amer. Biol. Teacher 25:409-411.



292713

AMRL-TDR-62-116

Biologistics for space systems symposium

may 1962

TECHNICAL DOCUMENTARY REPORT No. AMRL-TDR-62-116
October 1962

Biomedical Laboratory
6570th Aerospace Medical Research Laboratories
Aerospace Medical Division
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

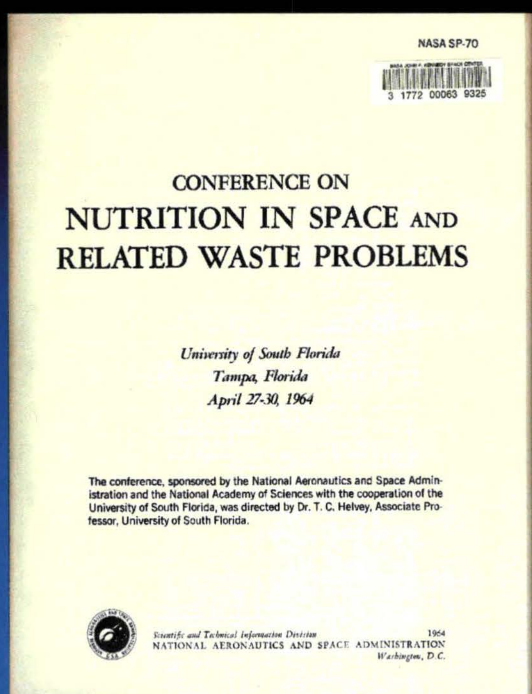
Biologistics for Space Systems Symposium

Wright-Patterson Air Force Base (1962)

419 pp with Chapters on :

- *Algal Gas Exchange*
- *Photosynthetic Mechanisms*
- *Waste Regeneration*
- *Nutritional Support in Bio-regenerative Systems*
- *Use of Higher Plants*

Lettuce
Chinese Cabbage
Cabbage
Cauliflower
Celery
Kale
Turnip
Endive
Dandelion
Swiss Chard
Radish
New Zealand Spinach
Tampala
Sweetpotato



NASA SP-70

3 1772 00063 9325

CONFERENCE ON
NUTRITION IN SPACE AND RELATED WASTE PROBLEMS

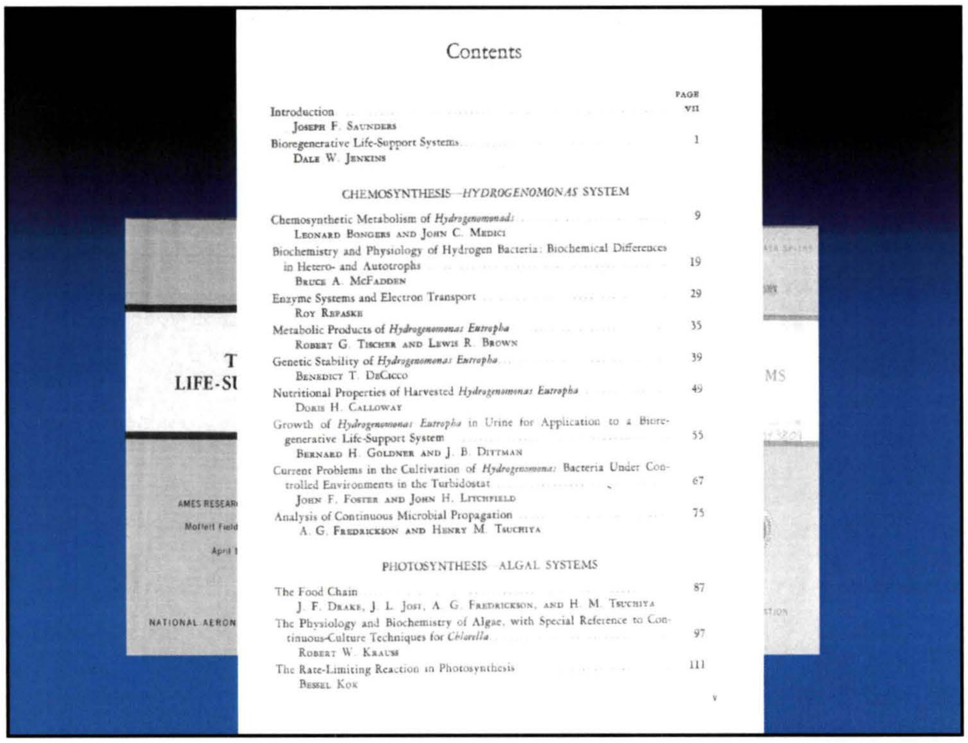
University of South Florida
Tampa, Florida
April 27-30, 1964

The conference, sponsored by the National Aeronautics and Space Administration and the National Academy of Sciences with the cooperation of the University of South Florida, was directed by Dr. T. C. Helvey, Associate Professor, University of South Florida.

Scientific and Technical Information Division 1964
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D.C.

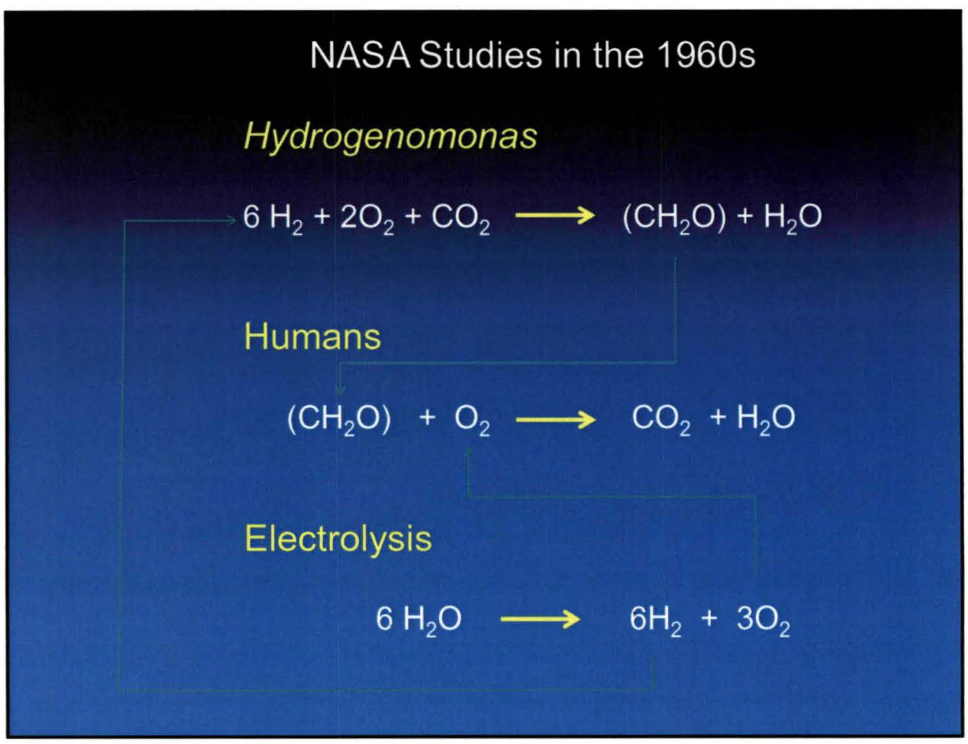
Closed Life Support:

NASA's Early Interests (1964)



Contents

v



NASA Studies in the 1960s
Hydrogenomonas
$6 H_2 + 2O_2 + CO_2 \longrightarrow (CH_2O) + H_2O$
Humans
$(CH_2O) + O_2 \longrightarrow CO_2 + H_2O$
Electrolysis
$6 H_2O \longrightarrow 6H_2 + 3O_2$

Photosynthesis in Space

Spirodela (duckweed) and *Chlorella*)

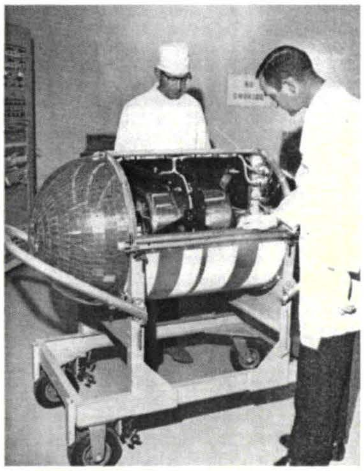
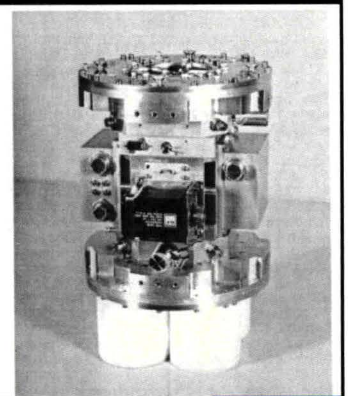
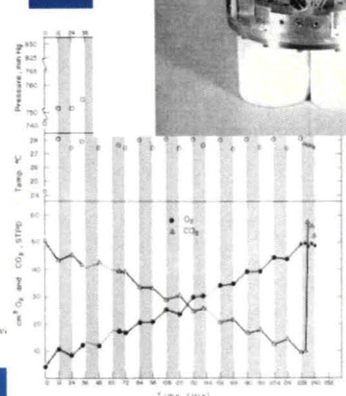


Fig. 11. Experimental apparatus mounted in OV1 satellite; note solar cell dome pow system.





C.H.Ward, S.S. Wilks, and H.L. Craft. 1970. Dev. Indust. Microbiol. 11:276-295

Bioregenerative Life Support for Space:

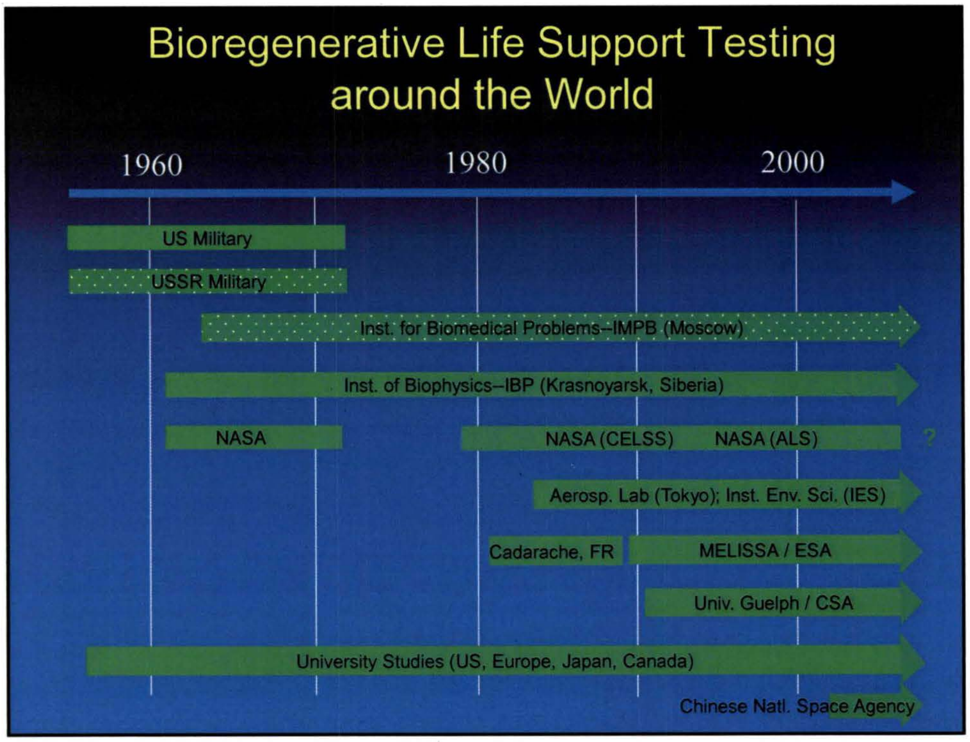
Some Reviews of Work in 1950s and 1960s:

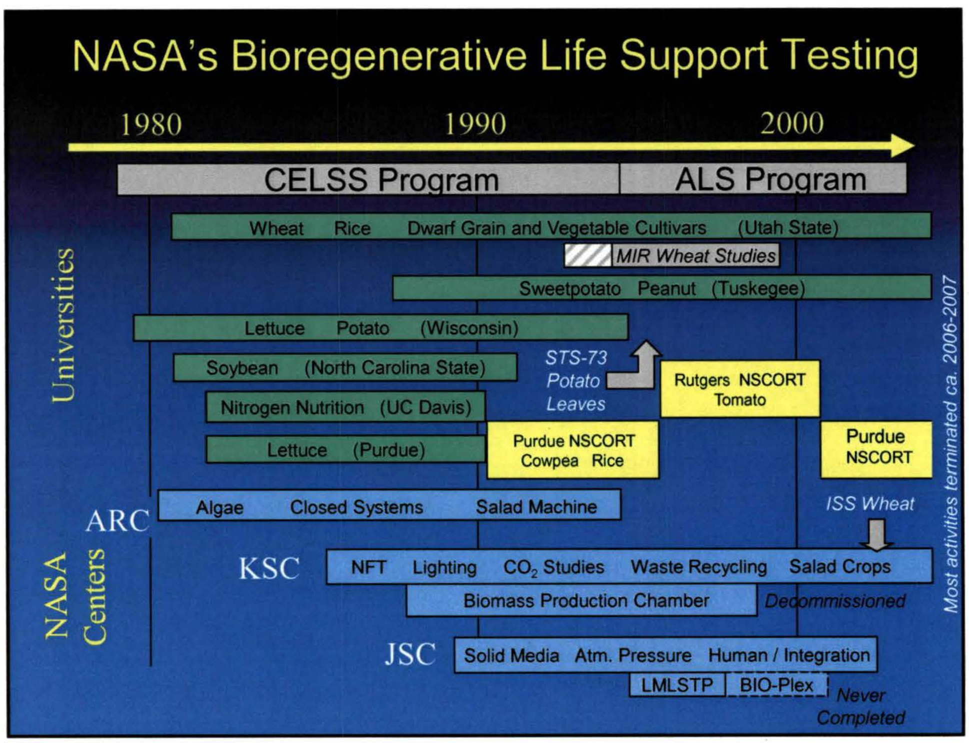
- Eley, J.H. and J. Myers. 1963. A study of a photosynthetic gas exchanger. A quantitative repetition of the Priestley Experiment. Texas J. Sci. 16:296-333.
- Miller, R.L. and C.H. Ward. 1966. Algal bioregenerative systems. In K. Kammermeyer (*ed.*) Atmosphere in Space Cabins and Closed Environments. Appleton-Century-Croft, NY.
- Taub, F.B. 1974. Closed ecological systems. *In*: R.F. Johnston, P.W. Frank, and C.D. Michener (*eds.*) Annual review of Ecology and Systematics. 5; 139-160.

Testing with Higher Plants and the CELSS Program

- Higher plants (crops) more acceptable as a food source
- Improved productivity of plants in controlled environment agriculture (CEA)
  - Hydroponic culture
  - HID Lighting
  - CO_2 enrichment
- Broad information base on agronomic spp.

Josef Gitelson and Henry Lisovsky at Bios 3 Facility in Krasnoyark, Siberia
Algae testing in 1960s and then primarily higher plants in 1970s and 1980s


Bioregenerative Life Support Testing around the World
1960
1980
2000
US Military
USSR Military
Inst. for Biomedical Problems–IMPB (Moscow)
Inst. of Biophysics–IBP (Krasnoyarsk, Siberia)
NASA
NASA (CELSS)
NASA (ALS)
?
Aerosp. Lab (Tokyo); Inst. Env. Sci. (IES)
Cadarache, FR
MELISSA / ESA
Univ. Guelph / CSA
University Studies (US, Europe, Japan, Canada)
Chinese Natl. Space Agency

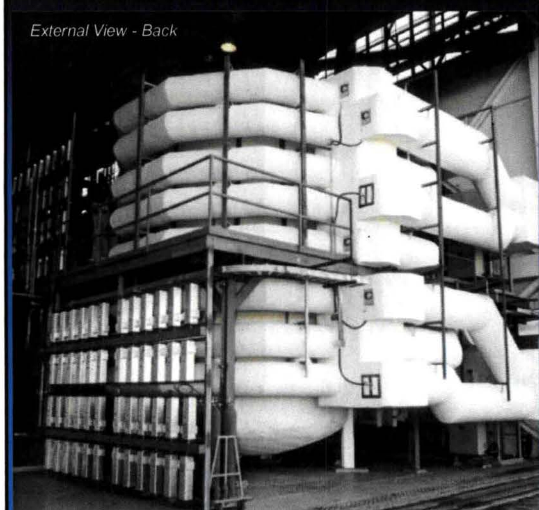

NASA's Bioregenerative Life Support Testing
1980
1990
2000
CELSS Program
ALS Program
Universities
Wheat Rice Dwarf Grain and Vegetable Cultivars (Utah State)
MIR Wheat Studies
Sweetpotato Peanut (Tuskegee)
Lettuce Potato (Wisconsin)
Soybean (North Carolina State)
STS-73 Potato Leaves
Rutgers NSCORT Tomato
Nitrogen Nutrition (UC Davis)
Lettuce (Purdue)
Purdue NSCORT Cowpea Rice
Purdue NSCORT
NASA Centers
ARC
Algae Closed Systems Salad Machine
ISS Wheat
KSC
NFT Lighting CO_2 Studies Waste Recycling Salad Crops
Biomass Production Chamber
Decommissioned
JSC
Solid Media Atm. Pressure Human / Integration
LMLSTP
BIO-Plex
Never Completed
Most activities terminated ca. 2006-2007

Some Crops for Life Support

Tibbitts and Alford [a]	Hoff, Howe, and Mitchell [b]	Salisbury and Clark [c]	Crops Used in BIOS-3 Testing [d]
Wheat	Wheat	Wheat	Wheat
Soybean	Potato	Rice	Potato
Potato	Soybean	Sweetpotato	Carrot
Lettuce	Rice	Broccoli	Radish
Sweetpotato	Peanut	Kale	Beet
Peanut	Dry Bean	Lettuce	Nut Sedge
Rice	Tomato	Carrot	Onion
Sugar Beet	Carrot	Rape Seed (Canola)	Cabbage
Pea	Chard	Soybean	Tomato
Taro	Cabbage	Peanut	Pea
Winged Bean		Chickpea	Dill
Broccoli		Lentil	Cucumber
Onion		Tomato	Salad spp.
Strawberry		Onion	
		Chili Pepper	

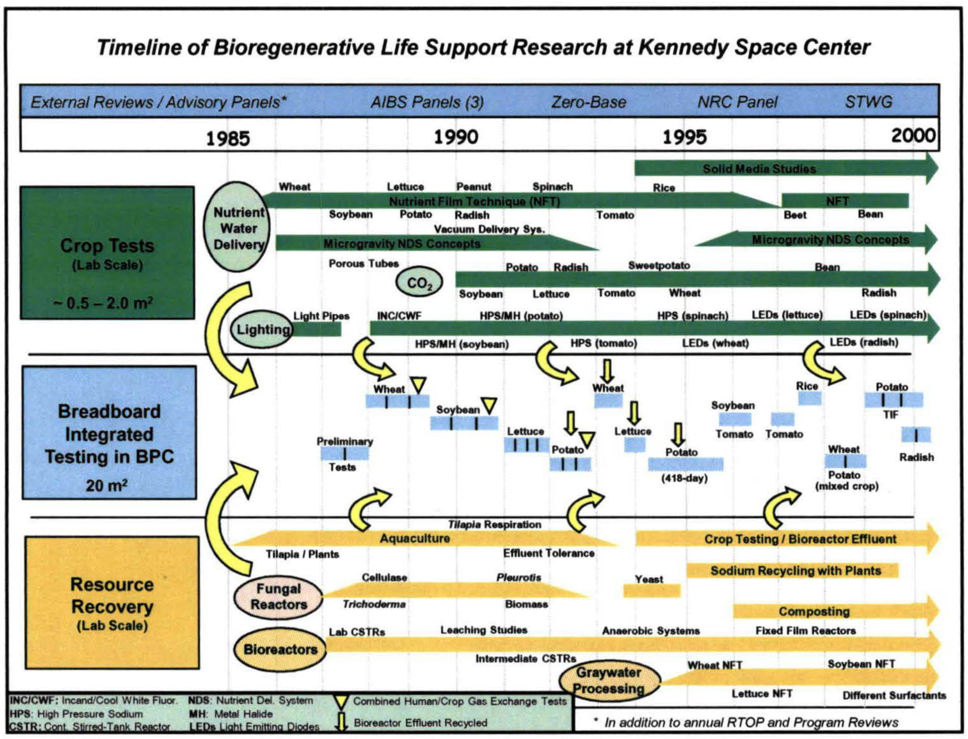
[a] Tibbitts and Alford (1982); [b] Hoff, Howe, and Mitchell (1982); [c] Salisbury and Clark (1996); [d] Gitelson and Okladnikov (1994)—diet also included supplemental animal protein and sugar.

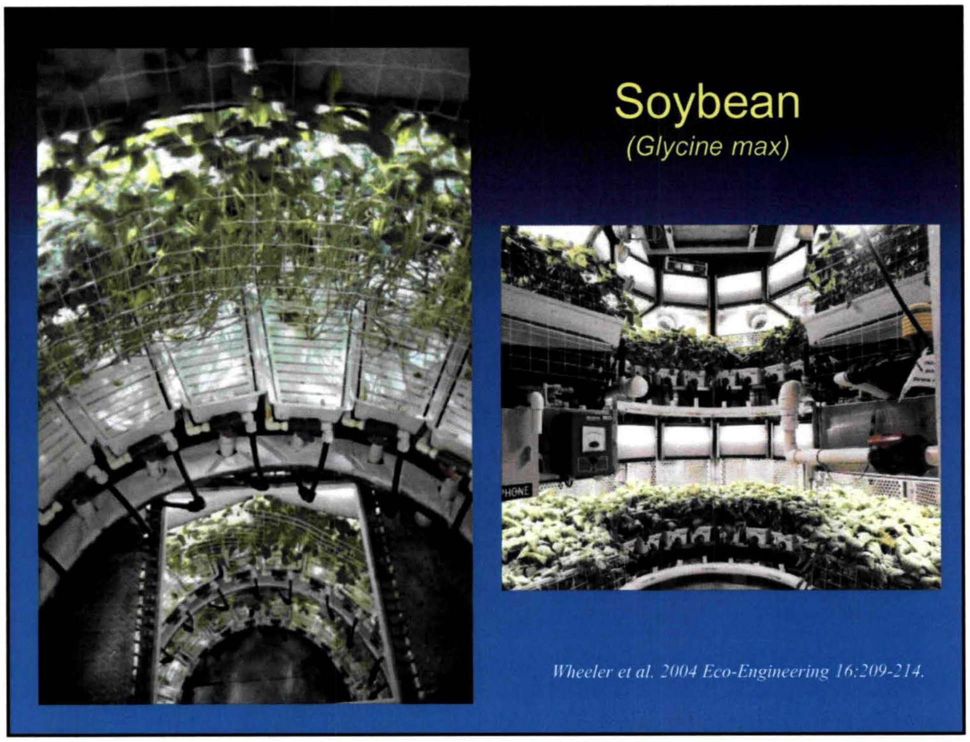
NASA's Biomass Production Chamber (BPC)

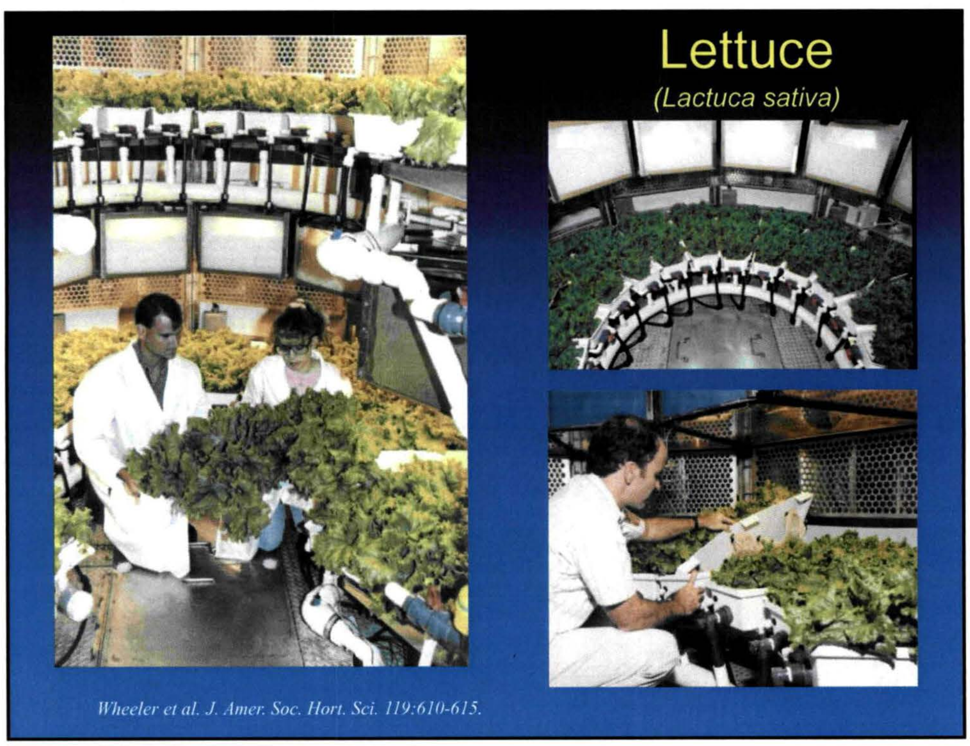


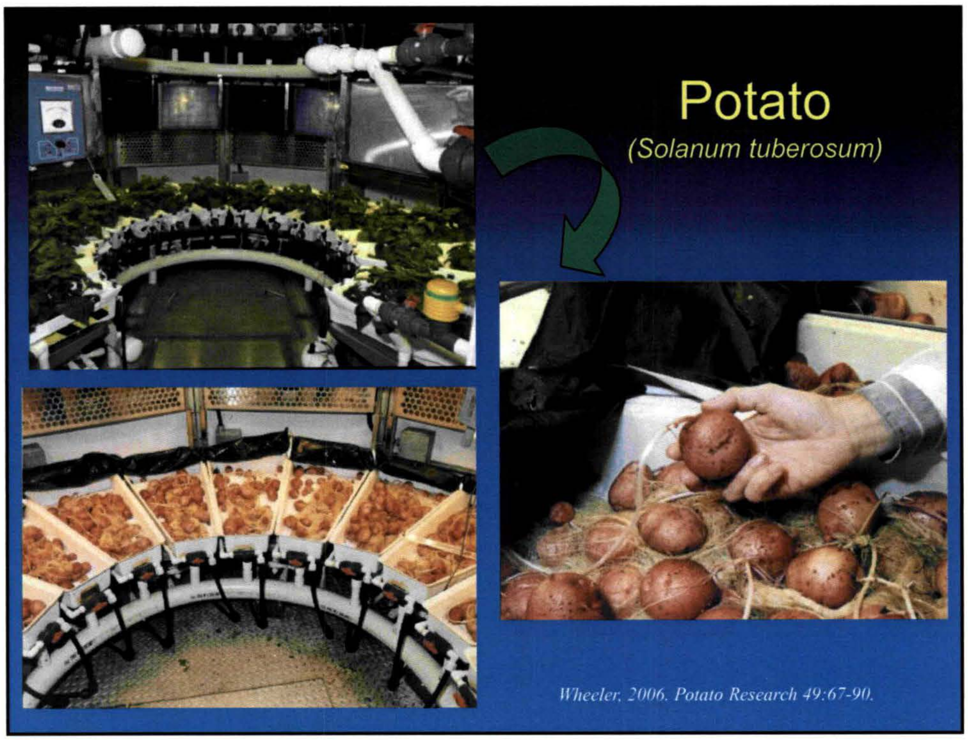
20 m^2 growing area; 113 m^3 vol.; 96 400-W HPS Lamps; 400 m^3 min^{-1} air circulation; two 52-kW chillers

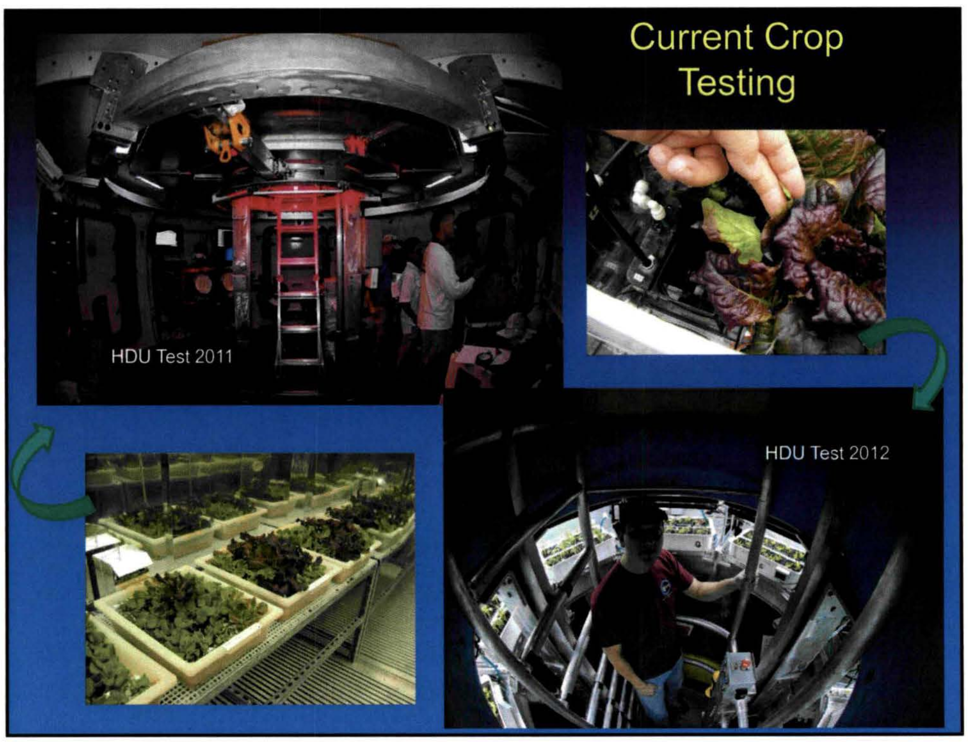

National Geographic Magazine, Nov. 1988.

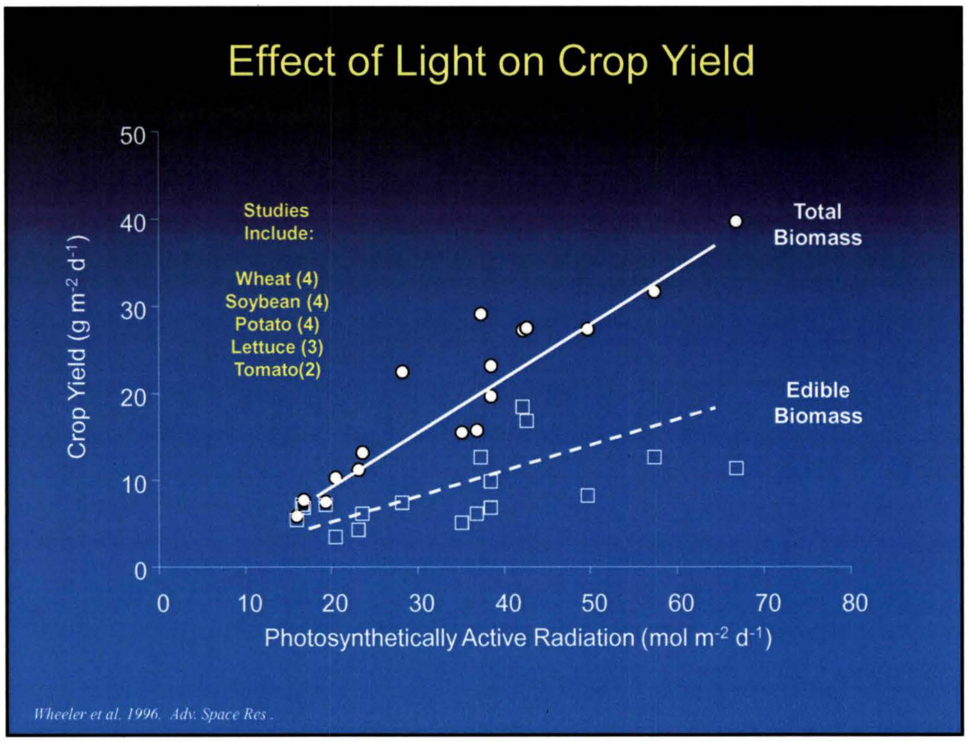

Timeline of Bioregenerative Life Support Research at Kennedy Space Center
External Reviews / Advisory Panels*
AIBS Panels (3)
Zero-Base
NRC Panel
STWG
1985
1990
1995
2000
Crop Tests (Lab Scale) ~ 0.5 – 2.0 m²
Nutrient Water Delivery
Solid Media Studies
Wheat
Lettuce
Peanut
Spinach
Rice
Nutrient Film Technique (NFT)
NFT
Soybean
Potato
Radish
Tomato
Beet
Bean
Vacuum Delivery Sys.
Microgravity NDS Concepts
Microgravity NDS Concepts
Porous Tubes
CO2
Potato
Radish
Sweetpotato
Bean
Soybean
Lettuce
Tomato
Wheat
Radish
Lighting
Light Pipes
INC/CWF
HPS/MH (potato)
HPS (spinach)
LEDs (lettuce)
LEDs (spinach)
HPS/MH (soybean)
HPS (tomato)
LEDs (wheat)
LEDs (radish)
Breadboard Integrated Testing in BPC 20 m²
Wheat
Soybean
Preliminary Tests
Lettuce
Potato
Wheat
Lettuce
Potato (418-day)
Soybean
Tomato
Tomato
Rice
Potato
TIF
Wheat
Potato (mixed crop)
Radish
Resource Recovery (Lab Scale)
Tilapia Respiration
Aquaculture
Tilapia / Plants
Effluent Tolerance
Crop Testing / Bioreactor Effluent
Fungal Reactors
Cellulase
Pleurotis
Trichoderma
Biomass
Yeast
Sodium Recycling with Plants
Composting
Bioreactors
Lab CSTRs
Leaching Studies
Anaerobic Systems
Fixed Film Reactors
Intermediate CSTRs
Graywater Processing
Wheat NFT
Soybean NFT
Lettuce NFT
Different Surfactants
INC/CWF: Incand/Cool White Fluor.
HPS: High Pressure Sodium
CSTR: Cont. Stirred-Tank Reactor
NDS: Nutrient Del. System
MH: Metal Halide
LEDs Light Emitting Diodes
Combined Human/Crop Gas Exchange Tests
Bioreactor Effluent Recycled
* In addition to annual RTOP and Program Reviews

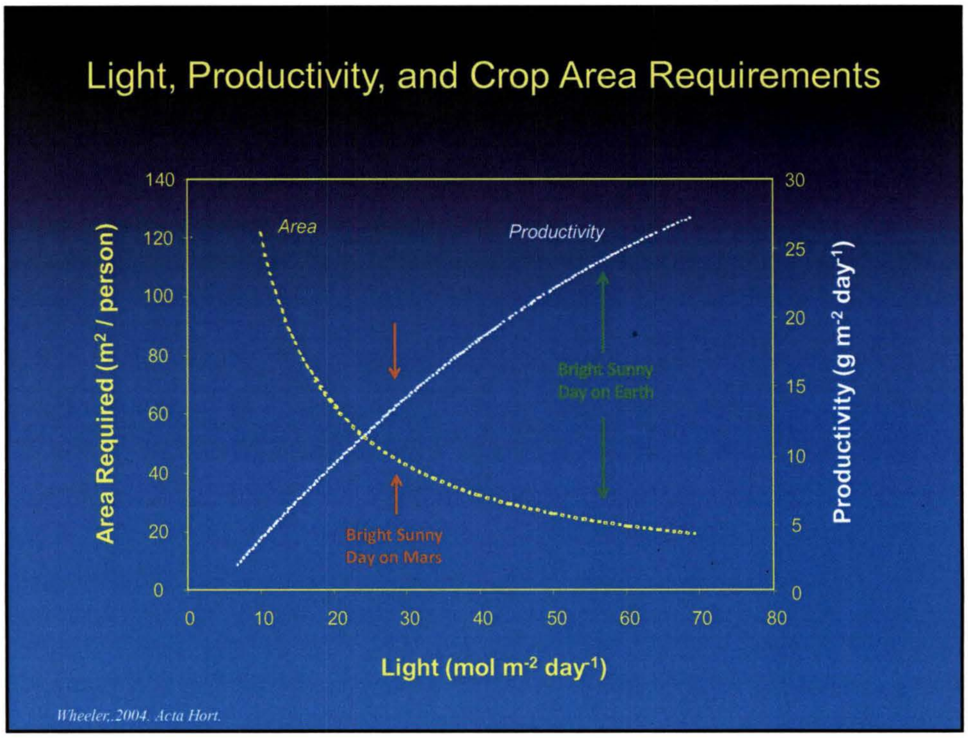

Soybean
(Glycine max)
PHONE
Wheeler et al. 2004 Eco-Engineering 16:209-214.


Lettuce
(Lactuca sativa)
Wheeler et al. J. Amer. Soc. Hort. Sci. 119:610-615.


Potato
(Solanum tuberosum)
Wheeler, 2006. Potato Research 49:67-90.


Current Crop Testing
HDU Test 2011
HDU Test 2012


Effect of Light on Crop Yield
Crop Yield (g m-2 d-1)
Studies Include:
Wheat (4)
Soybean (4)
Potato (4)
Lettuce (3)
Tomato(2)
Total Biomass
Edible Biomass
Photosynthetically Active Radiation (mol m-2 d-1)
Wheeler et al. 1996. Adv. Space Res.


Light, Productivity, and Crop Area Requirements
Area Required (m2 / person)
Productivity (g m-2 day-1)
Area
Productivity
Bright Sunny Day on Earth
Bright Sunny Day on Mars
Light (mol m-2 day-1)
Wheeler, 2004. Acta Hort.

Photosynthetic Radiation at Mars Surface over 2 Martian Years *(J. Clawson, 2006)*

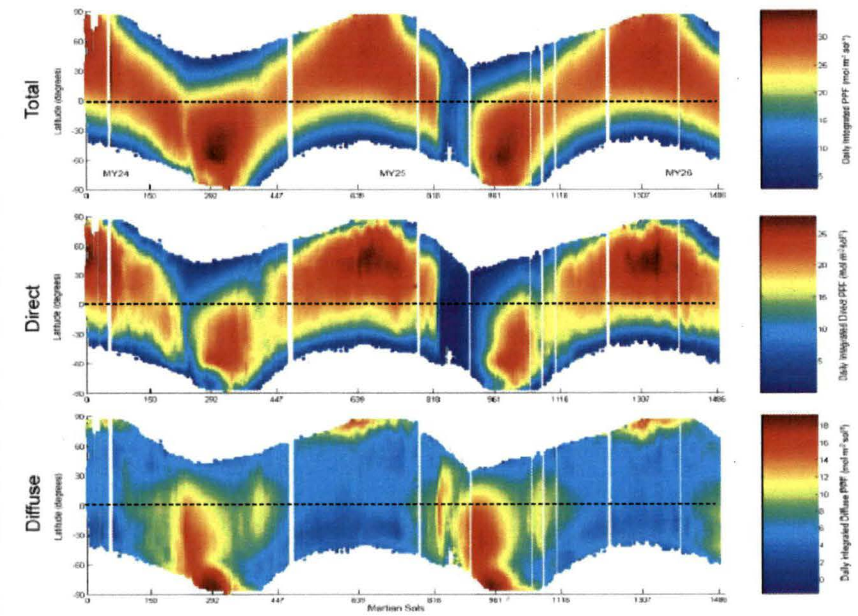
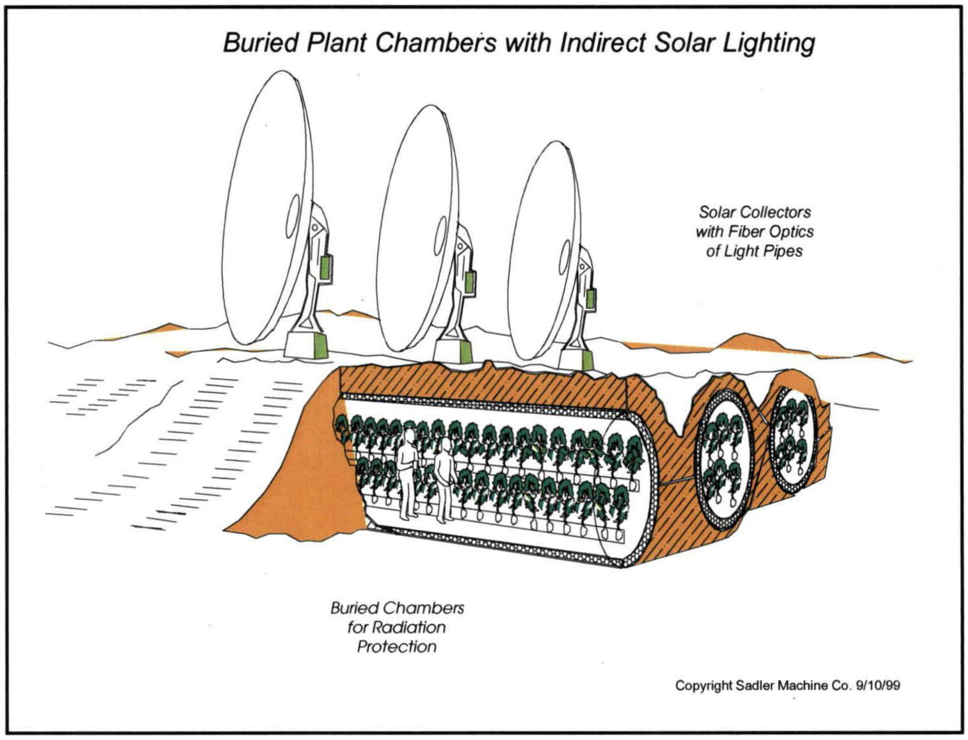


Figure 11 The daily integrated total, direct, and diffuse PPF versus latitude and Martian Sol for two Mars years. The labeled sols correspond to the start of each season on Mars. For example, sol 150 corresponds to the Northern Autumnal equinox.

Surface Deployable Greenhouse Concepts

→ Inflatable, low mass, easy stowage
→ Might be covered at night
→ Operated at low pressure

Rygalov et al. 2004. Habitation .


Buried Plant Chambers with Indirect Solar Lighting
Solar Collectors
with Fiber Optics
of Light Pipes
Buried Chambers
for Radiation
Protection
Copyright Sadler Machine Co. 9/10/99


Salad Machine Concept for Early Missions
Fresh Foods
Colors
Texture
Flavor
Antioxidants
Bright Light
Aromas
Gardening
Activity
MacElroy, R.D., M. Kliss, and C. Straight. 1992. Adv. Space Res.

Relaxation / Quiet Area by the Plant Chamber at US South Pole Station

View of Sitting Area (Anteroom) Adjacent to the Plant Chamber at US South Pole Station

Relaxation Area Adjacent to Plant Chamber at US South Pole Station

Photos courtesy of Lane Patterson and Phil Sadler, Univ. of Arizona

Essential Elements for Plants and Humans

Plants	Humans	
Nitrogen	Nitrogen	Sodium
Potassium	Potassium	Fluorine
Calcium	Calcium	Iodine
Magnesium	Magnesium	Selenium
Phosphorus	Phosphorus	Silicon
Sulfur	Sulfur	Chromium
Manganese	Manganese	Arsenic
Iron	Iron	Vanadium
Chlorine	Chorine	Tin
Zinc	Zinc	
Copper	Copper	
Molybdenum	Molybdenum	
Nickel	Nickel	
Boron		

Humans require more micronutrients and relatively high sodium levels in comparison to plants. Recycling human wastes (e.g. urine) to plants could result in sodium build-up.

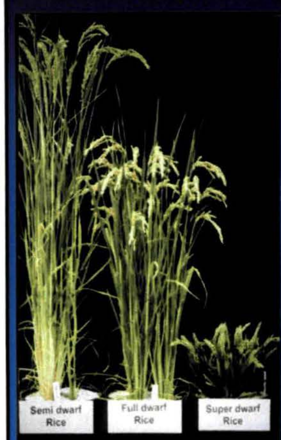
Wheeler, 2000. In: Lane and Schoeller (eds.) Nutrition in space flight and weightlessness models.

Sodium Recycling in Closed Systems

Beets and chard are capable of storing sodium in edible tissues (leaves).

Subbarao et al. 2003. Critical Reviews of Plant Sciences 22 (5): 391-416.

Cultivar Selection and Development



<u>Several Universities:</u>
Cultivar Comparisons
(wheat, potato, soybean, lettuce, sweetpotato, tomato

<u>Utah State University:</u>
Super Dwarf Wheat
Apogee Wheat
Perigee Wheat
Super Dwarf Rice

<u>Tuskegee University:</u>
ASP Sweetpotato (GMO)
⇨ 3 X total protein and starting cultivar

Higher Plants to Support 1 Human

(Includes Food, O_2, CO_2 Removal and Water Purification)

→ ($20\ g\ m^{-2}\ d^{-1}$ dwt yield) x ($4\ kcal\ g^{-1}$)
 $= 80\ kcal\ m^{-2}\ d^{-1}$

→ ($2500\ kcal\ person^{-1}\ d^{-1}$) / ($80\ kcal\ m^{-2}\ d^{-1}$)
 $= 31\ m^2\ person^{-1}$

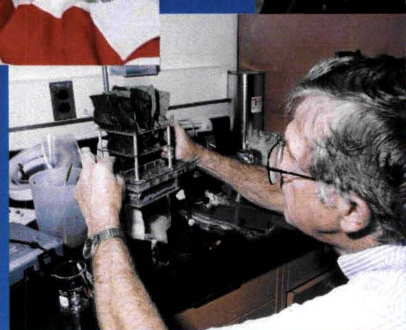
…$40\ m^2$ / person

→ Japanese IES Studies, 100-120 m^2 / person for more complete dietary needs.

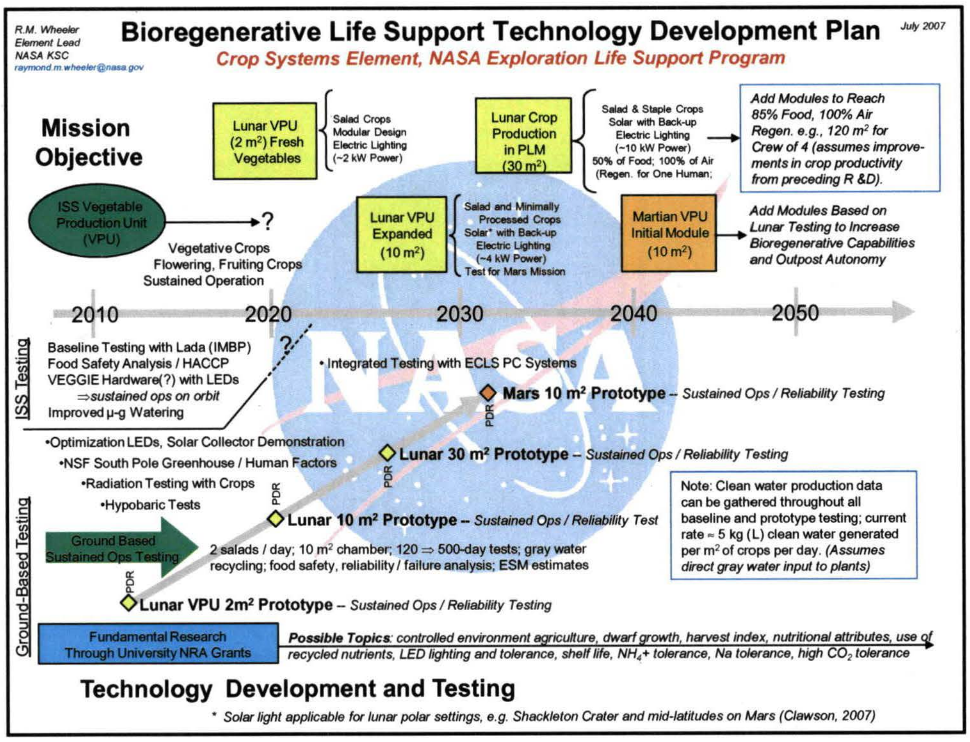
Space Flight Experiments

Mizuna in Lada on ISS

Wheat in SVET on MIR



Potato Leaves on STS-73 in Astroculture



NASA Contingent of Researchers Visiting Russia (1989)


Questions ?


Waste Water
Treatment Systems
Plants for
Purifying
Gray Water
Bioreactors
for Water
Processing
Morales et al. 1996. FEMS Microbial Ecol.
Rector et al. 2007. J. Membrane Sci